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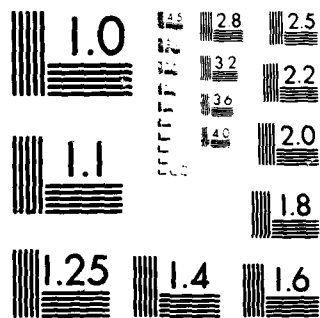
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DEVELOPMENT OF A NEW DESIGN PROCEDURE FOR OVERLAND FLOW SYSTEM. (U)  
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DEVELOPMENT OF A NEW DESIGN PROCEDURE  
FOR OVERLAND FLOW SYSTEM

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INTRODUCTION

In 1971 the U.S. Army Corps of Engineers conducted five comprehensive studies on the feasibility of regional wastewater management systems for large urban areas. Each study identified land application as a viable means for wastewater treatment and disposal. However, the Corps soon determined that the technology for designing and operating land application systems was inadequate. As a result, the Corps initiated a land treatment research and development program in 1972, and the Cold Regions Research and Engineering Laboratory (CRREL) was designated as the lead laboratory. This program was successfully completed in 1980 and much of the research provided information for updating the Corps/EPA/USDA/DOI Process Design Manual for Land Treatment of Municipal Wastewater (16). Although this research program has been completed, the Corps continues to support a center of land treatment expertise at CRREL for continued technology transfer and assistance to Divisions and Districts.

The three methods of land application studied under the research and development program were slow rate, rapid infiltration and overland flow. The slow rate method is quite similar to agricultural irrigation in that wastewater is applied to farms, fields and forests at a rate which produces no runoff. The rapid infiltration method is similar to natural sand filtering and can only be used when sandy or gravelly soils are available.

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was initiated in 1972, overland flow was the least developed method of land application.

An overland flow system consists of a series of grassy terraces which are carefully graded so that wastewater flows downslope in a thin sheet. Gated pipe, troughs or sprinklers are used to uniformly distribute the wastewater at the top of each terrace. Renovation occurs as the wastewater travels over the soil surface, and the volume of wastewater is reduced because of evapotranspiration and percolation. The remaining runoff is collected in a shallow ditch at the base of the terrace and discharged to a receiving stream. When properly designed and managed, the runoff water quality from an overland flow system can easily meet secondary effluent standards.

Overland flow was initially developed in this country back in the early fifties by the Campbell Soup Co., which used this process for treating high-strength cannery wastes. Their success encouraged the Environmental Protection Agency (EPA) to evaluate overland flow as a process for treating municipal wastewater. Studies conducted at the EPA Laboratory in Ada, Oklahoma, by Thomas et al. (15) confirmed that the process was effective in renovating municipal wastewater. However, little was known about the operational limits of overland flow and the only procedure available for design was based on general guidelines and rules-of-thumb. Thus, a primary objective of the Corps research effort was to test the limits of overland flow performance and develop a more rational procedure for design. This research effort was conducted at both CRREL and the U.S. Army Engineer Waterways Experiment Station (WES).

The new design procedure developed as a result of this research is based on reactor kinetics, a concept familiar to most environmental engineers. In the case of overland flow, the reactor is the soil surface where various physical, biological and chemical reactions take place. As in conventional process design, the controlling parameter is detention time. For overland flow, detention time is the average time a unit volume of water takes to travel from the top to the bottom of the terrace. The desired level of treatment can be achieved by controlling the length of time that wastewater remains in contact with the soil surface. With this approach, overland flow systems can be constructed for a wide range of site conditions as long as detention time requirements are met.

#### DESCRIPTION AND OPERATION OF CRREL OVERLAND FLOW TEST SITE

The data used to develop the hydraulic and kinetic design relationships were obtained from the CRREL overland flow test site. This site, which has been in operation since June 1977, is 30.5 m long x 8.8 m wide (0.03 ha) and graded to a 5% slope. It is subdivided into three equal



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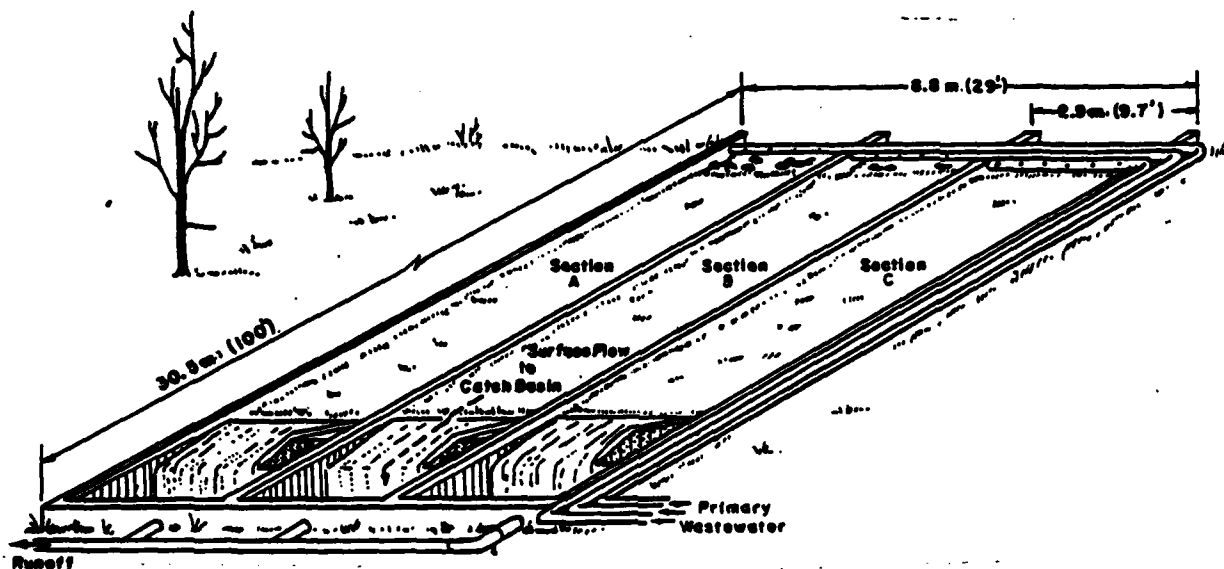


Figure 1. Schematic of CRREL overland flow test site.

sections designated A, B and C so that parallel studies can be conducted. Underlying the soil at a depth of 15 cm is a 30.0-mil-thick rubber membrane, which was installed to prevent downward percolation. The grass cover on the site is a mixture of many species including K-31 tall fescue, orchardgrass, Kentucky bluegrass and quackgrass (10). The grass was harvested on the average of once every six weeks during the growing season. A schematic of the site is shown in Figure 1.

Undisinfected primary effluent was applied to the overland flow test site during the entire study. Perforated plastic pipe was used to distribute wastewater along the top of each section, and a bed of crushed stone placed beneath the pipe helped to uniformly disperse the flow. The quality of the primary effluent is shown in Table 1.

The application rate was monitored and controlled by means of a constant head weirbox. Five application rates ranging from 0.35 to 1.20 m<sup>3</sup> hr<sup>-1</sup> were tested. The application cycle was 7 hr on, 17 hr off for 5 days per week. At these application rates and this cycle, the equivalent hydraulic loading rates were 13.8 to 46.7 cm wk<sup>-1</sup>. Each application rate was evaluated for a period of approximately 6 weeks. All sections were operated simultaneously at the same application rate. Because of leaks in the membrane along the outside boundary, wastewater applications to section A were discontinued during 1979.

Table 1. Quality of applied primary effluent.

Parameter	Mean	Standard deviation	No. of observations
BOD ( $\text{mg L}^{-1}$ )	72	23	58
Total suspended solids ( $\text{mg L}^{-1}$ )	59	30	98
Ammonia ( $\text{mg L}^{-1}$ as N)	24	6	99
Total phosphorus ( $\text{mg L}^{-1}$ as P)	6.6	2.2	33

Runoff was collected at the base of each section in individual galvanized steel catch basins. A small submersible sump pump located in each basin discharged the runoff into a drainage ditch. The volume of runoff was recorded by flowmeters attached to the discharge lines. During this study, the average runoff rate was 75, 87 and 89% of the application rate for sections A, B and C, respectively.

All measurements of detention time and water quality sampling were conducted during periods of hydraulic steady-state operation. The hydraulic steady-state period began when the runoff rate stabilized, and it terminated when application was stopped. The amount of time needed to reach hydraulic steady state varied depending on antecedent moisture conditions.

Hydraulic detention time was determined by measuring the travel time of a chloride tracer. Chloride was selected because it is conservative and easily analyzed. A tracer solution was made by dissolving 94.6 g of sodium chloride in 3 L of distilled water. The sodium chloride solution was added as a "slug addition" to the distribution chamber in the constant head weirbox. Composite samples were taken of the runoff at various intervals and analyzed for chloride. Chloride concentrations were then plotted vs time, and the peak of the response curve was chosen to represent detention time. An example of a chloride response curve is shown in Figure 2. The detention time in this case was 40 min for an application rate of  $0.6 \text{ m}^3 \text{ hr}^{-1}$ . Altogether, 50 detention times were measured at the CERREL site during this study.

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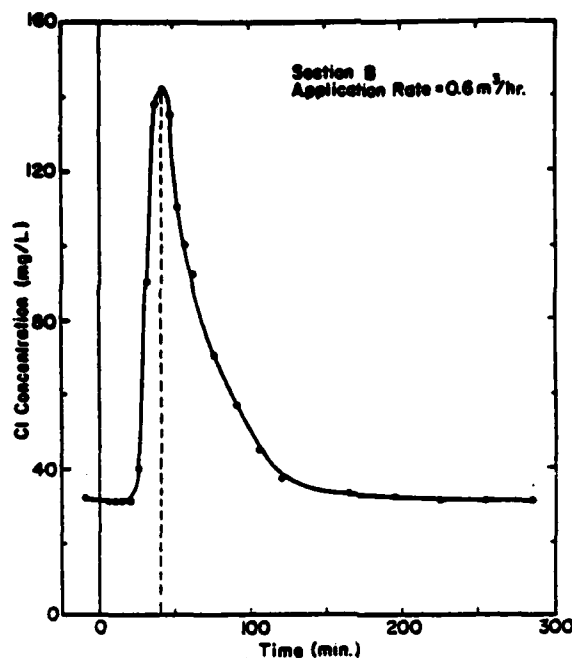


Figure 2. Typical chloride response curve for measuring detention time.

#### DEVELOPMENT OF THE HYDRAULIC DETENTION TIME RELATIONSHIP

At a well designed and operated overland flow site, water flows down-slope as a thin sheet until it freefalls into a runoff collection ditch. Under these conditions, the overland flow system can be considered to operate in the laminar flow regime (4). For the simplest case of overland flow over a smooth surface, the average velocity  $v_s$  can be described by the following equation (8):

$$v_s = \frac{g S d^2}{3 \nu} \quad (\text{m s}^{-1}) \quad (1)$$

where  $g$  = gravitational constant,  $9.81 \text{ m s}^{-2}$   
 $S$  = slope,  $\text{m m}^{-1}$   
 $d$  = average depth of flow,  $\text{m}$   
 $\nu$  = kinematic viscosity,  $\text{m}^2 \text{ s}^{-1}$ .

For an actual overland flow system, resistance to flow will be greater because of the grass and vegetative litter. Therefore, the aver-

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age overland flow velocity  $V$  will be lower than the smooth surface velocity  $v_s$  and can be expressed as

$$V = \alpha v_s \text{ (m s}^{-1}\text{)} \quad (2)$$

where  $\alpha$ , the resistance coefficient, is less than 1.0. Substituting eq 2 into eq. 1, the velocity of flow over an overland flow terrace can be described by

$$V = \alpha \left[ \frac{8 S d^2}{3 v} \right] \text{ (m s}^{-1}\text{)} \quad (3)$$

If one assumes that most of the water flows in a straight path down-slope, the velocity  $V$  can be expressed as

$$V = \frac{L}{\bar{t}} \text{ (m s}^{-1}\text{)} \quad (4)$$

where  $L$  is the length of terrace in meters, and  $\bar{t}$  the hydraulic detention time in seconds. Also, from the continuity equation, the average depth of flow  $d$  can be determined by

$$d = \frac{Q \bar{t}}{L W} \text{ (m)} \quad (5)$$

where  $Q$  is the average overland flow rate ( $\text{m}^3 \text{ s}^{-1}$ ) and  $W$  the width of the terrace in meters. Substituting eq 4 and 5 into eq 3 and rearranging terms, detention time can be calculated from the relationship

$$\bar{t} = \left[ \frac{3 v W^2}{\alpha g S Q^2} \right]^{1/3} L. \quad (6)$$

In more convenient terms, where the average detention time is described in minutes ( $\bar{T}$ ) and the average overland flow rate ( $q$ ) in  $\text{m}^3 \text{ hr}^{-1} \text{ m}^{-1}$  of width, eq 6 becomes

$$\bar{T} = 5.65 \left[ \frac{v}{\alpha g} \right]^{1/3} \frac{L}{s^{1/3} q^{2/3}}. \quad (7)$$

Assuming a kinematic viscosity of  $0.112 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$  (at  $15.6^\circ\text{C}$ ) and substituting the value of the gravitational constant  $g$ , eq 7 becomes

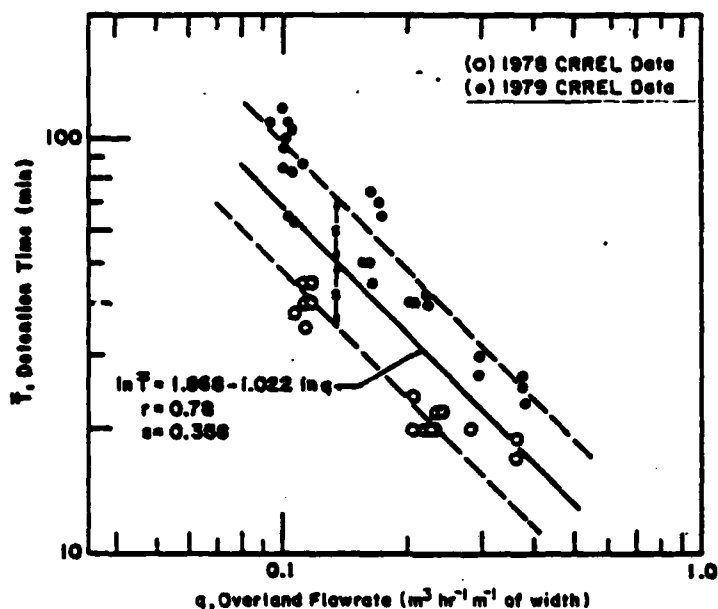


Figure 3. Overland flow rate vs detention time for CRREL overland flow test site.

$$\bar{T} = 0.0274 \frac{L}{\alpha^{1/3} S^{1/3} q^{2/3}} \quad (8)$$

To determine the resistance coefficient  $\alpha$ , eq 8 was evaluated using data obtained from the CRREL overland flow test site. For each CRREL test section, the values of  $L$  and  $S$  are 30.5 m and 0.05 m m<sup>-1</sup> respectively. Substituting these values, eq 8 can be simplified to

$$\bar{T} = \frac{2.27}{\alpha^{1/3} q^{2/3}} \quad (9)$$

By plotting detention time vs the average overland flow rate on log-log paper,  $\alpha$  can be determined from the line of best fit. This was done for the CRREL data as shown in Figure 3. A regression analysis indicates good correlation ( $r = 0.78$ ) between application rate and detention time. However, the standard deviation is large, indicating that detention time varied considerably for a given overland flow rate. Most of this deviation appears to be caused by a difference in results obtained between the 1978 and 1979 growing seasons. The equation for the line of best fit shown in Figure 3 is

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$$\ln \bar{T} = 1.868 - 1.022 \ln q \quad (10)$$

or

$$\bar{T} = \frac{6.48}{q^{1.022}} \quad (11)$$

Substituting eq 11 for  $\bar{T}$  in eq 9, an expression for the resistance coefficient is

$$\alpha = 0.043 q^{1.066} \approx 0.043 q \quad (12)$$

This expression indicates that the resistance coefficient  $\alpha$  increases in direct proportion to the average overland flow rate. This relationship can be explained by the fact that, as the flow rate increases, the depth of flow also increases. On the irregular surface of most overland flow terraces, increasing the depth causes more surface area to be wetted, which increases the resistance to flow. This hypothesis is consistent with visual observations at the CRREL site and several other overland flow sites.

Substituting eq 12 back into eq 8, the final form of an empirical relationship for predicting detention time is

$$\bar{T} = \frac{0.078 L}{S^{1/3} q} \quad (13)$$

This equation indicates that  $T$  is directly proportional to  $L$  and inversely proportional to  $q$ . Slope, being to the one-third power, is less significant although it cannot be considered negligible. For example, assuming  $L = 50$  m and  $q = 0.2 \text{ m}^3 \text{ hr}^{-1} \text{ m}^{-1}$ , an increase in slope from 2 to 12% would decrease detention time from 72 to 40 minutes, a decrease of 44%.

To determine the validity of eq 13, detention times were measured at two other overland flow sites. The first site, located near Utica, Mississippi, was a research facility operated by the U.S. Army Engineer Waterways Experiment Station (WES). This site (no longer in operation) had 24 terraces, each 45 m long by 4.5 m wide and slopes of 2, 4, and 8% (11). The second site is located indoors at the University of California at Davis. Each laboratory scale terrace is 6 m long x 1.5 m wide and set at a 4% slope (14). A combined total of 40 detention time measurements were taken at both sites.

Statistical analysis of these data indicated that the average difference between predicted and measured detention times was only 8 minutes.

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In most cases the measured detention time was longer than predicted, which allows an extra margin of safety in the design. In a Student's *t* distribution, the difference between measured and predicted detention time was not significant at the 95% level. Therefore, eq 13 appears to adequately describe the average hydraulic characteristics of overland flow. However, day-to-day differences varied considerably. This is understandable, considering the variability of the surface microtopography from one terrace to another. Construction techniques, patterns of vegetative growth and harvesting operations are also factors which can change the hydraulic detention time.

## DEVELOPMENT OF THE KINETIC RELATIONSHIPS

Kinetic relationships describing removal of biochemical oxygen demand (BOD), total suspended solids (TSS), ammonia ( $\text{NH}_3\text{-N}$ ) and total phosphorus (total P) were developed by taking several detention time measurements during each application period. The average detention time ( $\bar{T}$ ) was then calculated along with the average percent removal on a mass basis for each constituent.

### BOD removal

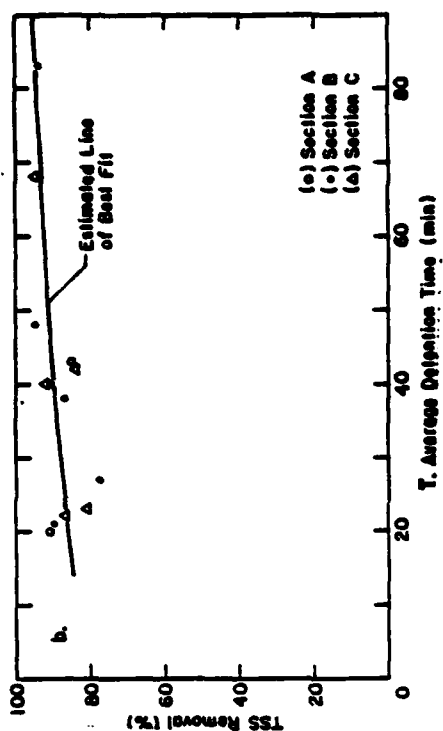
BOD is removed by sedimentation, filtration and biological oxidation (16). The first two mechanisms are responsible for removing particulate BOD. The soluble BOD is oxidized by microorganisms which are probably similar to the attached biomass found in trickling filters. However, some soluble organic compounds are released from the plant-soil system and, as a result, runoff BOD concentrations below 3 to 5  $\text{mg L}^{-1}$  should be expected (9).

Temperature also has an effect on runoff BOD concentrations. Martel et al. (5) found that BOD concentrations in the runoff exceeded 30  $\text{mg L}^{-1}$  at soil temperatures at or below 4°C. However, temperature effects should not be a significant problem at full-scale facilities if wastewater is stored during the winter. In this study, temperature effects were nullified by selecting performance data obtained during the growing season only (April through October).

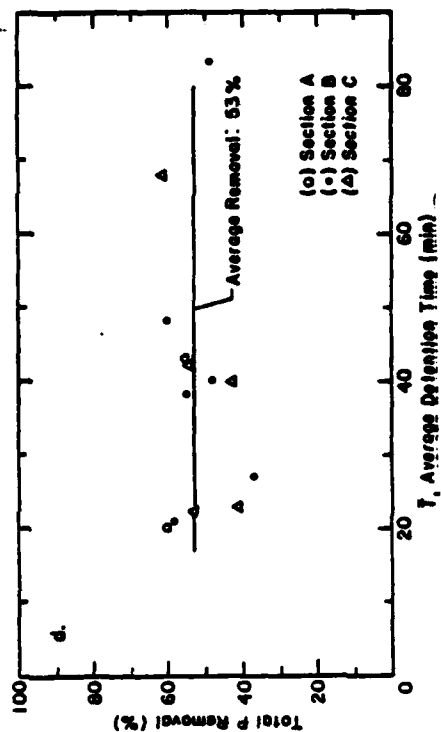
Data obtained at both CRREL and the U. of California, Davis (Fig. 4a) indicate that BOD removal can be expressed as a first-order equation in the form

$$\text{Percent removal} = (1 - A e^{-k\bar{T}}) 100 . \quad (14)$$

The coefficients *A* and *k*, obtained by a least-squares fit to the data, were 0.52 and 0.03  $\text{min}^{-1}$ , respectively. The coefficient *k* is the average



b. TSS.



c.  $\text{NH}_3\text{-N}$ .

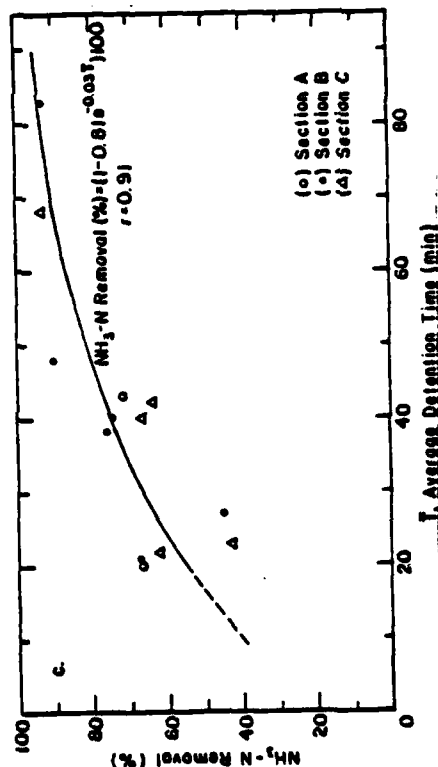


Figure 4. Kinetic relationships for BOD, TSS,  $\text{NH}_3\text{-N}$  and Total P removal.

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kinetic rate constant. The coefficient A can be interpreted as the non-settleable fraction of BOD in the applied wastewater while the remaining settleable fraction (0.48) is removed during the first few meters or minutes after wastewater is applied.

### TSS Removal

Total suspended solid (TSS) removal vs average detention time from the CRREL site is shown in Figure 4b. The flat slope of the estimated line of best fit indicates that TSS removal changed little over the range of detention times tested. For example, at a detention time of 20 minutes, TSS removal was 86%. A three-fold increase in detention time (60 min) only increased removal by 6%.

The high solids removal efficiency of the overland flow process is due to the shallow depth of water and the long travel distance to the end of the terrace. Even minute particles with slow settling velocities are able to settle out before reaching the collection ditch. Also, grass and vegetative litter help to entrap and filter out particles.

The solids removal relationship developed in this study (Fig. 4b) applies to fecal types of solids only. Removal of algal solids found in lagoon effluent is more difficult to predict. Data from the Easley, South Carolina, site indicated that algae removal by overland flow is marginal (12). However, Peters et al. (11) report good removal of algae at low application rates.

### Nitrogen Removal

A number of mechanisms are involved in nitrogen removal, including volatilization, nitrification-denitrification, adsorption, plant uptake and soil storage. The ammonia form of nitrogen can be removed by any of the above mechanisms. Most of the organic nitrogen is initially removed by sedimentation and then incorporated into the soil or converted to ammonia by saprophytic bacteria. Nitrate is the most difficult form of nitrogen to remove (13, 18). Nitrate ions have little affinity for soil particles and thus are not retained on the overland flow terrace.

This study focused on the kinetics of ammonia removal because it is the nitrogen form of most concern in discharge limitations. The correlation between ammonia removal and detention time obtained from CRREL data is shown in Figure 4c. The first-order equation which closely fits these data ( $r = 0.91$ ) is also shown in Figure 4c. For ammonia removal the coefficients A and k were 0.81 and  $0.03 \text{ min}^{-1}$ , respectively.

It is interesting to note that both BOD and ammonia removal equations (see Fig. 4a and 4c) contain the same kinetic rate constant ( $k = 0.03 \text{ min}^{-1}$ ), suggesting that both BOD and ammonia removal are controlled by the

rate-limiting step. It is unlikely that both substrates would have the same removal rate constant; a more likely explanation is that removal is mass transport limited. In other words, the rate of mass transport from the bulk liquid to the active biomass and adsorption sites is the mechanism governing removal rate. This reasoning is reinforced by the fact that overland flow operates in a laminar flow regime, which reduces opportunities for substrate contact with reactive sites.

#### Phosphorus removal

Phosphorus is removed primarily by sorption to soil particles. On level and flow terraces only surface exchange sites are available because the wastewater passes over the soil surface rather than through it. As a result, the exchange sites are used up rather quickly, and the removal of phosphorus by overland flow systems is limited. Plant uptake is another mechanism capable of removing phosphorus. Palazzo et al. (10) reported that forage grasses removed 54% of the applied phosphorus at the test site.

As shown in Figure 4d, phosphorus removal did not change significantly over the range of detention times tested. Percentage removals ranged from 37 and 61% and averaged 53%. Analyses of runoff samples indicated that most of the total phosphorus was in the "ortho" form, which indicates that the phosphorus removed was tied up with particulate matter. As discussed earlier (see TSS removal), particulate matter was easily removed by overland flow.

#### Validation

The kinetic relationships for removal of BOD, TSS and  $\text{NH}_3\text{-N}$  were validated by comparing the predicted removal to the actual removal recorded at seven full-scale systems. Statistical analysis of these data indicated that the average differences between predicted and actual BOD, TSS and  $\text{NH}_3\text{-N}$  removal were only 1.9, -2.0 and 2.8%, respectively, for systems receiving primary or raw wastewater (see Table 2). These results confirm that the kinetic relationships for BOD and TSS removal are valid for overland flow systems receiving primary or raw wastewater. The lowest inlet concentration of BOD and TSS where these relationships hold is estimated to be  $45 \text{ mg L}^{-1}$ . Different kinetic relationships need to be developed for overland flow systems receiving secondary or pond effluent.

#### CONCLUSION

The hydraulic and kinetic relationships developed during this study are used as the basis of a rational procedure for design of overland flow systems. The three basic steps in this procedure are

Table 2. Predicted vs actual removal efficiencies on overland flow systems receiving primary or raw wastewater.

System	Calculated detention time (min)	Runoff frac.	Applied conc. (mg L <sup>-1</sup> )		Predicted removal (%)		Actual removal (%)		Predicted- actual removal (%)	
			BOD	TSS	NH <sub>3</sub> -N	BOD	TSS	NH <sub>3</sub> -N	BOD	TSS
Ada, Okla. (15)	222	0.50	150	160	17.0	99+	95+	99+	96	97
	195	0.50	150	160	17.0	99+	95+	99+	97	98
	171	0.50	150	160	17.0	99+	95+	99+	97	98
Pauls Valley, Okla. (2)	294	0.50	117	105	17.0	99+	95+	98	96	97
									91	91
Werrabee Farm, Aust. (13)	626	0.80	507	233	31.0	99+	95+	99+	98	93
									20*	20*
Easley, S.C. (12)	59	0.70	200	186	19.4	91	92	86	91	97
									85	85
Paris, Tex. (1)	138	0.60	480	181	--	99	95+	--	99	96
									--	--
Mean									1.9	-2.0
Std. deviation									1.3	2.2

\* Wastewater was applied during the winter when crops were not actively growing.

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1. Determine the detention times required to remove pollutants specified in the discharge permit (~~Figs. 4a, b, c, d~~).
2. Calculate the application rate needed to satisfy the longest or most critical detention time, (~~eq. 13~~).
3. Calculate the land area required from the application rate and system design flow.

These three steps are discussed in further detail by Martel et al. (7). Examples of how to use the procedure can be found in the new Process Design Manual for Land Treatment of Municipal Wastewater (16) and Martel et al. (6, 7).

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